

Turbulent Dissipation Challenge

A community Driven Effort

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The Goal

The goal of the present document is to present the idea of, and convince the community to participate in, Turbulent Dissipation Challenge. The idea was discussed in Solar Heliospheric and Interplanetary ENvironment (SHINE) 2012 meeting. The proponents of the idea Tulasi Parashar and Chadi Salem have prepared this document to circulate the idea in the community.

The "Turbulent Dissipation Challenge" idea is to bring the community together and simulate the same set of problems and try to come to a common set of conclusions about the relative strengths of two different kinds of dissipative processes (current sheets/ reconnection sites vs. wave particle interactions). To take the challenge further, the simulators will provide artificial spacecraft data from the simulations for the observers to analyze.

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1 Motivation

The nature of fluctuations at the kinetic scales in the solar wind is of interest to better understand its dynamics. Whether these fluctuations are highly nonlinear or whether an important degree of linearity exists is a matter of open debate at present. The ultimate answer to this debate will have important implications for global solar wind modeling and in turn for our space weather models.

One important question regarding the kinetic fluctuations in the solar wind, that needs to be answered, is the nature of dissipative mechanisms. Most of the dissipative mechanisms can be broadly grouped into two categories:

i) Wave particle interactions (**WPI**) like the cyclotron damping or Landau Damping of Kinetic Alfvén Waves (e.g. Barnes (1968, 1969); Hollweg and Isenberg (2002); Araneda et al. (2008); Bale et al. (2005); Gary et al. (2006, 2005); Gary and Saito (2003); Tu and Marsch (1995); Howes et al. (2008, 2011) and references therein).

ii) Particle energization by coherent structures (**CS**) (e.g. heating by current sheets and/or reconnection sites Matthaeus et al. (1984); Dmitruk et al. (2004); Drake et al. (2006); Sundkvist et al. (2007); Retinò et al. (2007); Parashar et al. (2011); Osman et al. (2011); Wan et al. (2012); Osman et al. (2012); Perri et al. (2012); Karimabadi et al. (2013)).

Depending on the plasma conditions, different dissipative mechanisms can be dominant at the kinetic scales. It is a topic hotly debated in the space physics community. The discussion of these mechanisms covers physics questions like coronal heating and acceleration of the solar wind (e.g. Dmitruk and Gmez (1997); Dmitruk et al. (2004); De Moortel et al. (2008); Cranmer and van Ballegoijen (2003); Verdini et al. (2009); Chandran et al.

(2010); Chandran (2010); Parashar et al. (2011); Hansteen and Velli (2012)), in situ heating of the solar wind (e.g. Cranmer et al. (2009)), turbulence in the magnetosphere (e.g. Eastwood et al. (2009)) and turbulence at the heliosheath to name a few. This question is inherently related to other kinetic aspects like the role of instabilities in shaping the velocity distribution function and shape of the power spectrum at the kinetic scales. High temperature anisotropies can induce plasma instabilities which can tend to isotropize the velocity distribution function and also can generate "in situ" plasma waves (e.g. Gary (2005); Gary and Saito (2003); Matteini et al. (2010); Matteini et al. (2011) and references therein). The nature of the fluctuations present at the kinetic scales not only decides what kind of dissipative processes are important but also the shape of the power spectrum at those scales (e.g. Bale et al. (2005); Narita and Gary (2010); Alexandrova et al. (2012); Perez et al. (2012); Boldyrev and Perez (2012) and references therein). The question of turbulent dissipation has to be answered in the light of all the associated kinetic aspects.

Sometimes the debate about the dissipative processes in the solar wind ends up being side-tracked to a discussion about whether there are waves in the solar wind or not. Given the variability of the solar wind, one would expect these processes to be active at any given time or place in the solar wind. We feel that the direction of the community effort should be towards a better understanding of the relative strengths and weaknesses of such processes under different circumstances. For this we propose the community driven effort Turbulence Challenge.

The basic idea is to have different simulation modelers do the exact same problem (as was done for example in GEM Challenge) and compare results to come to a common set of conclusions agreed upon by the community. To take it further, the modelers will provide artificial data to observers who will analyze the data using their techniques. Having a slightly better idea of what is going on in the simulations, we will be able to constrain the observational techniques. This comparison with observations will also provide the modelers a direction towards the physics that is of more relevance in the solar wind.

2 Major Questions to be Answered

Given the complicated nature of the system there are many questions to be addressed. *The list below represent only what appears to us as being directly relevant to the question of dissipation and is not meant to be a comprehensive list of all the important questions.* These are all different aspects of one global question of understanding the turbulence in the Solar wind but given the complications related to the system, we will treat them as questions that can partly be treated independent of other questions. We propose to start with one question from the following list and suggest involving a community effort in that direction.

1. The nature of the turbulent cascade in the inertial range. How the cascade of energy to smaller scales happens is still a matter of open debate. In the community there are many studies trying to correlate the slope of the magnetic field spectrum with the turbulent cascade being Kolmogorov or Irochnikov-Kraichnan or Goldreich-Sridhar like (e.g. Biskamp (1994); Chandran (2005, 2008b,a). The nature of the cascade is closely related to the form of modes in which energy is available at the kinetic scales and in turn the relative importance of different dissipative processes. In a magne-

tized plasma, the turbulence evolves in such a manner that most of the energy is in fluctuation modes perpendicular to the mean field (e.g. Zweben et al. (1979); Shebalin et al. (1983); Oughton et al. (1994); Goldreich and Sridhar (1995); Tu and Marsch (1995); Matthaeus et al. (1990); Bieber et al. (1996) etc. and the references there in). This means that there is not much energy in the parallel wave vectors for cyclotron resonance. The answer to this puzzle lies in the details of how the cascade proceeds in the inertial range and how it ends at the kinetic scales. Many methods have been suggested to provide significant power at parallel wave-vectors (e.g. Velli (1993); Chandran (2005, 2008b); Cranmer and van Ballegooijen (2003); Markovskii et al. (2006) and many others). The mechanisms vary and a question remains whether the resulting fluctuations at kinetic scales are still highly nonlinear, (supporting low frequency energization mechanisms), or if a certain degree of linearity persists, (supporting wave particle interactions). If these fluctuations are linear in nature, whether these are Kinetic Alfvénic fluctuations or Whistler like fluctuations is another matter of open debate (e.g. Voitenko and Goossens (2006); Salem et al. (2012); Narita and Gary (2010); Saito et al. (2010); Podesta and Gary (2011); Schekochihin et al. (2009)).

2. Another important aspect is the nature of dissipative processes in the solar wind. The details of this question are inherently related to the answer of first question above. Arguments have been made in favor of localized low frequency heating mechanisms like current sheet and reconnection site heating (e.g. Dmitruk et al. (2004); Parashar et al. (2011); Osman et al. (2011) and references therein) and also in the favor of distributed processes like wave particle interactions (e.g. Howes et al. (2008); Gary and Saito (2003) and many more). We can "start exploring" this question even without a detailed answer to the first question. It can actually provide valuable information to help answer the first question. This is where the present proposal of Turbulence Challenge comes in. Different groups will do the same set of simulations using different simulation techniques and compare the results. The simulations will be aimed at reducing the effect of the nature of the cascade in inertial range. We will vary the initial conditions to match different possibilities arising because of the nature of turbulent cascade in the inertial range.
3. Recent developments in the kinetic studies of the solar wind measurements have brought in the discussion of the nature of the fluctuations below the ion inertial scales. Whether the fluctuations are dissipative or dispersive or both is a matter of open debate. How the "cascade" proceeds to the electron scales from the proton scales is also not well understood. The nature of the cascade, whether it is power law or exponential, is also being debated (e.g. Sahraoui et al. (2009, 2010); Alexandrova et al. (2009, 2012) and references therein). This directly relates to the dynamic processes and fluctuation types i.e. KAWs or Whistlers (e.g. Howes et al. (2008); Gary et al. (2008, 2010) and many others).

This proposal concentrates on the details of question 2.

3 The Turbulent Dissipation Challenge

As discussed briefly in point two of last section, we propose to address the question of turbulent dissipation. *This question is inherently tied to the other two questions posed in the last section but it can be addressed in certain limits and can provide valuable insights to better address those questions.* We propose that for studies in the kinetic regime, we start with the following question:

Question: At ion kinetic scales, under the same physical “idealized” conditions, what is the relative strength of the two kinds of dissipative processes? Is it wave particle interactions or current sheets and reconnection sites that energize the plasma more efficiently?

A few constraints are required to address the above question properly.

1. **Parameters:** The plasma parameters and boundary conditions vary a lot depending on where we are in the sun-earth system. So the dominant physical processes would be very different at different places. So we suggest to fix one set of conditions to make the setup unambiguous.
2. **Kinetic Processes:** Depending on the nature of the turbulent cascade in the inertial range, the nature of fluctuations available at the kinetic scales could be very different. The nature of the cascade from ion scales to electron scales could also affect the dominant processes at the kinetic scales. As both these questions are unanswered, we suggest to keep the system size small enough to eliminate the possibility of large scale cascade affecting the dynamics at the proton scales. This way the largest scale dynamics in our problem would be the ion kinetic processes. The variations in the nature of fluctuations available at ion kinetic scales can be used a different initial conditions.
3. **Problem Setup:** One approach could be to set up a system where both kinds of processes compete with each other but it would be very hard to separate the contributions from different processes during the analysis.

We suggest a slightly different approach where we set up two systems in which the two processes do not compete but one or the other dominates. This by setting up comparable systems we can compare the relative strength of such systems.

The first step we propose is to set up two 2.5D initial value problems. Both simulations will be decaying initial value problems. All the parameters of these simulations will be exactly the same. The only difference between the runs would be the initial conditions and the direction of the mean magnetic field. A third open setup is suggested for the participant groups to add to the discussion generated by the first two setups.

Justification for 2.5D: *Of course the solar wind is three dimensional and 2D is not the answer to the final problem. We might miss some effects in such limits but that adds to the point of this set up that we want to isolate the action of various processes. If we do 3D simulations as the first step, it will be almost impossible to separate the effects of CS or WPI. We propose this as a*

starting point because it appears relatively easy to separate these processes in 2D. In 2D, based on the direction of the mean field, either CS or WPI will dominate the energy budget. Once we have an understanding of the relative importance of such processes in the idealized conditions, we can design 3D simulations to better address this question.

The size of the simulations would be kept at very small physical dimensions (only a few c/ω_{pi}) in order to eliminate the effects of the inertial range turbulent cascade which is different in 2D as compared to 3D. This way the dominant dynamics at the largest scales in the simulations is expected to be the dissipative mechanism at the ion kinetic scales. Also, having smaller physical box size gives us the potential of resolving the system very well with today's computational powers.

3.1 Choice of Physical Parameters

The solar wind dynamics varies a lot with time and location (slow wind, fast wind, transient structures etc). We could expect different dissipative processes dominating the energy budget in such different conditions. In general it could be a mix of different processes with some processes being more important than the others under a given set of conditions. This makes the choice of the physical parameters very important.

We propose that for the first step we fix the conditions we want to study to, for example, typical fast wind conditions at 1AU as observed by the WIND spacecraft, and/or, typical slow wind conditions as observed by the cluster spacecraft. The advantages of using one spacecraft over the other can be discussed at the conference session on this topic. The exact interval can be chosen by the involved observers once the project gets started.

3.2 Choice of Initial Conditions

To isolate the effects of WPI or CS, we propose two 2.5D simulations with the same set of plasma parameters but different direction of mean magnetic field and different initial conditions. Both simulations will be a few c/ω_{pi} in each direction (with very large spatial grids to well resolve the system). We describe the two different setups below.

- Run 1 will have out of plane mean field and also highly nonlinear initial condition. This is closer to 2D strong turbulence and will eliminate the possibility of parallel or highly obliquely propagating waves (as defined w.r.t. the mean field). It has been shown that in this setup, waves have a minimal energy budget and current sheets are directly correlated to plasma heating (e.g. Parashar et al. (2011)).
- Run 2 will have in plane mean magnetic field and a spectrum of waves as initial condition (e.g. Hellinger et al. (2003) and others). Such a case will minimize current sheet formation and will be dominated by wave particle interactions. When set up in the kinetic codes, this set up will have a possibility of a host of kinetic wave modes (KAWS, whistlers etc.) interacting with the plasma to produce wave particle resonances.
- Run 3 will be an open slot for people to make their own setup in which the two kinds of processes are expected to compete with each other.

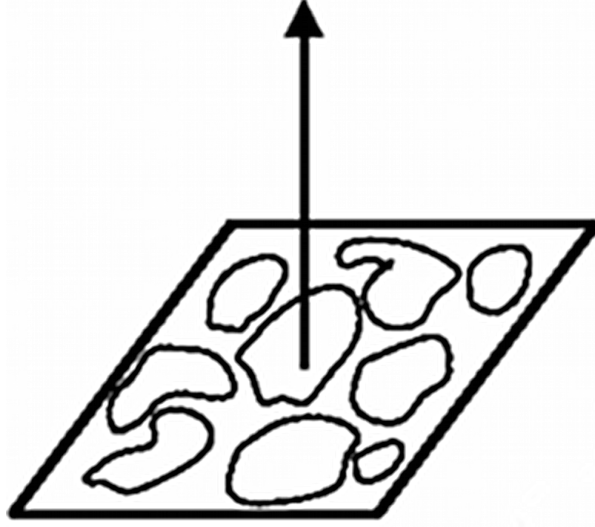


Figure 1: Set up with highly nonlinear fluctuations and mean field out of the plane of simulation. In such a setup, intermittent dynamics like current sheets and reconnection sites would dominate the plasma energization budget.

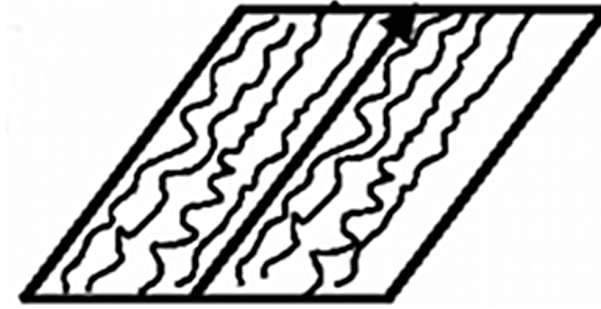


Figure 2: Set up with mean field in the plane of simulation and a spectrum of waves as the initial condition. In this setup, we expect wave particle interactions to dominate the energy budget.

The two set ups will separate the action of CS and WPI in the kinetic regime. If all simulation techniques find out the same answer as far as comparison of heating rates in these two setups is concerned, we will come to the very important fundamental conclusion of which processes are more efficient in heating the plasma under idealized conditions. The next step can be taken to mix the two kind of processes to see if we can empirically describe the dissipation as a combination of heating rates of CS and WPI in the idealized limits.

3.3 Simulation Techniques to Involve

At present there are a large number of computer codes available to do such simulations. As far as kinetic codes are concerned, Particle in Cell (PIC) (e.g. Malakit et al. (2010); Wu and Shay (2012); Bowers et al. (2008); Camporeale and Burgess (2010)), Hybrid PIC (e.g. Parashar et al. (2009); Vasquez and Markovskii (2012); Verscharen et al. (2012)), Vlasov (e.g. Valentini et al. (2010); Servidio et al. (2012)), Gyrokinetics (e.g. Howes et al. (2008)) are a few models that come to mind right away. There are also fluid models with collisionless kinetic physics modeled in them (e.g. Passot et al. (2012)). It would be ideal to have all the groups participate in the challenge. This way not only we will have a comparison of results from codes with different physics but also a cross comparison of different codes with the same physics.

Groups with fluid simulation models are also encouraged to participate. By comparing the heating rates out of fluid models by varying the artificial or empirically modeled dissipation, we might be able to find out a way to mimic realistic dissipation in fluid simulations.

We realize that setting up 2D simulations is very tricky in Reduced MagnetoHydroDynamics (RMHD) and Gyrokinetics. We propose that they can still participate in the challenge by (assuming x, y plane to be the plane of simulation) having the same condition for all z values. This way the initial condition would be uniform in z and will mimic the 2.5D initial conditions. The evolution of the system will have the out of plane couplings of the wave vectors but these simulations will add to the overall conclusion and will provide invaluable clues to set up initial 3D runs.

3.4 Artificial Observations

Artificial satellite data from the simulations will be created and provided to the observers to analyze. Different data analysis from different groups will enable us to pinpoint the physics required to mimic realistic data in our simulations. As in the case of simulations, it will be ideal to involve as many observers as possible.

4 Time Line and Management Plan

We propose to make the challenge a multi step process. We begin with the simplest set up and proceed towards more complex set ups. A possible road map could be like this:

- Set up very simple 2.5 dimensional (2.5D) problems trying to isolate the strength of different dissipative processes for the same parameter regime. The initial phase would include a set of simulations (all initial value, decaying turbulence problems) designed to have one kind of dissipative processes dominant (if possible only mode of dissipation).

We repeat the simulations for different set ups and compare the strengths of these dissipative processes in idealized set ups where they do not compete with other dynamical processes. Once we have a reasonable understanding of their relative strengths, we move on to set up more complicated problems.

- steps 2) to N-1) Intermediate steps of the road map will be decided on the progress made and the interest of the community.
- The final set up would be to do more realistic three dimensional simulations using different models and building up on the earlier work done by the Turbulence Challenge participants.

4.1 Data Output and Sharing

We propose that the data be output in the same format. We propose plain double precision unformatted time sequences in direct access files. This can be easily done in post processing and the codes do not have to be modified to do this. A small few lines code can read the specific code output and write it as simple double precision unformatted and vice versa.

Data output from different models will be shared on a common platform where different groups can analyze data from out her groups and compare different runs using different analysis tools. Each group will provide the short codes to convert common data to their favorite format and back. Doing the analysis this way, we can compare how different analysis techniques extract different physics out of these runs.

Different kinds of artificial data (single point measurements, multiple point measurements etc.) will be provided to the observers to perform their analysis and compare the results to real solar wind data.

4.2 Conference Sessions and Publications

We will be proposing a session in Solar Heliospheric and INterplanetary Environment (SHINE) 2013 workshop on this subject where things can be discussed by the community members in detail.

Depending on the participation in the challenge, we could arrange for a special issue with a journal and have all the papers by individual groups published in the special issue.

4.3 Project Management and Computer Time

Many detailed points have to be cleared and sorted out before the project can start. This being a community driven effort, a lot of input has to come from all the participants. As far as general management is concerned, the proponents of this idea (Tulasi Parashar and Chadi Salem) volunteer to do so.

We have already had a wiki set up for this purpose and also created a mailing list. People interested in participating in the challenge should send an email to *turbochallenge-subscribe@lists.physics.udel.edu* to be added to the mailing list and wiki, where further detailed discussions will be held.

The project will require substantial amount of computer time and we plan on getting dedicated computer time for this project. Discussions with from Air Force Research Laboratory, Maui are under way and hopefully common platform for doing the simulations and sharing data can be provided by them. Initial input from Dr. Jeffrey Yepez of AFRL,

Maui, indicates that getting a few million dedicated hours of computer time should be possible to kick start the project.

5 Summary

A good understanding of the kinetic processes at work in turbulent collisionless plasmas is of central importance to not only the Solar Wind community but to Solar, Magnetospheric, Astrophysics as well as Fusion communities. A proper understanding of the system would require a lot more effort but we hope that this problem would prove to be a simple yet significant step forward in that direction.

As a first step, we propose that the comparison be between Wave Particle Interactions and energization by coherent intermittent structures as two classes of dissipative mechanisms. The question of relative strengths of different wave particle interactions (e.g. Landau Damping of KAWs vs Whistlers or cyclotron damping) can be a further step in the challenge.

6 Acknowledgements

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While we have tried to include only representative papers in references, any major exclusions (if any) are not intentional.

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